Air Force Materiel Command

Developing, Fielding, and Sustaining America's Aerospace Force

Truths, Darn Truths, and Statistics

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Presented at the

NASA Statistical Engineering Symposium

Williamsburg, VA

3-5 May, 2011

U.S. AIR FORCE

I n t e g r i t y - S e r v i c e - E x c e l l e n c e
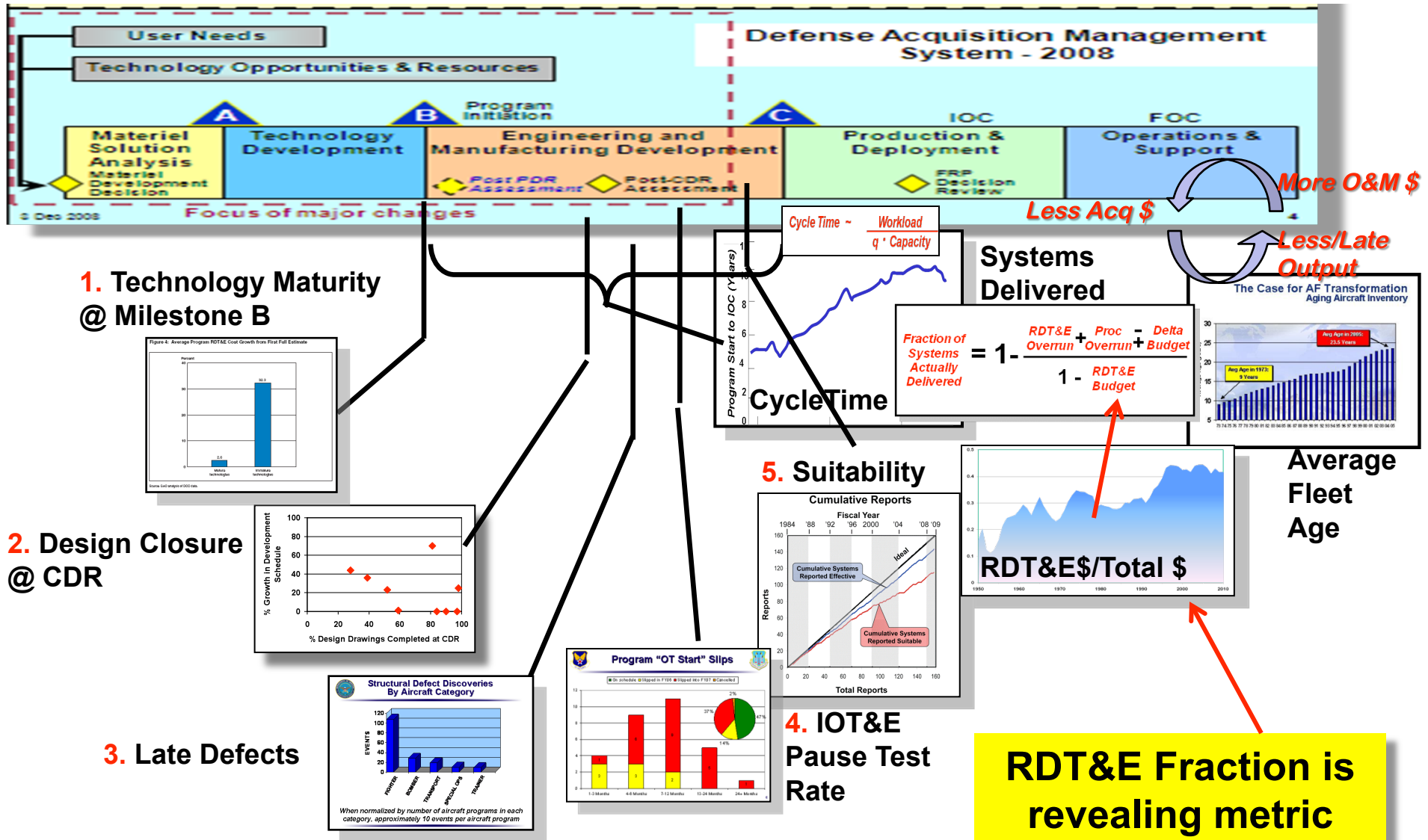
Objective

- **Shift image from lies, damn lies, and statistics to**
  - ➢ **<u>Truth</u> – right answer achieved in an experiment**
  - ➢ **<u>Darn Truth</u> – defined risk at key leverage points in acquisition**
  - ➢ **<u>Statistics</u> – disciplined approach to identifying and managing risk**

It is less about statistical theory and more about how we increase systems engineering effectiveness during defense acquisition using statistical tools

Targeting Five Key Leverage Points
Marked by Events – Mired by Lack of Effectiveness

Defense Acquisition Management System - 2008

User Needs

Technology Opportunities & Resources

A — Materiel Solution Analysis — Material Development Decision

B — Program Initiation — Technology Development

Engineering and Manufacturing Development — Post PDR Assessment — Post CDR Assessment

C — Production & Deployment — FRP Decision Review — IOC

FOC — Operations & Support

Focus of major changes

8 Dec 2008

More O&M $
Less Acq $
Less/Late Output

1. Technology Maturity @ Milestone B

2. Design Closure @ CDR

3. Late Defects

$$\text{Cycle Time} \sim \frac{\text{Workload}}{q \cdot \text{Capacity}}$$

Cycle Time

5. Suitability

4. IOT&E Pause Test Rate

Systems Delivered

$$\text{Fraction of Systems Actually Delivered} = 1 - \frac{\text{RDT\&E Overrun} + \text{Proc Overrun} - \text{Delta Budget}}{1 - \text{RDT\&E Budget}}$$

RDT&E$/Total $

Average Fleet Age

The Case for AF Transformation — Aging Aircraft Inventory

RDT&E Fraction is revealing metric

Acquisition Cycle Time
Key T&E Effectiveness Parameter

$$Cycle\ Time \sim \frac{Workload}{q \cdot Capacity}$$

- *Workload* – **Process driven, currently ~22,000 of wind tunnel testing and 13,000 of propulsion cell testing**

- *q (inverse of rework)* – **Process driven, typically have 10 structural failures found in flight; control surface resizing**

- *Capacity* – **Budget driven, availability x staffing x throughput**

50% reduction in wind tunnel costs equates to just a few tenths of a percent reduction in program costs – Reducing acquisition cycle time by a month could save more than the cost of the entire wind tunnel campaign

Kraft, Edward M. " Integrating Computational Science and Engineering with Testing to Re-engineer the Aeronautical Development Process," AIAA Paper 2010-0139 , January, 2010.

Kraft, Edward M. and Huber, Arthur F II "A Vision for the Future of Aeronautical Ground Testing," The ITEA Journal of Test and Evaluation, Vol 30, No 2, June 2009.

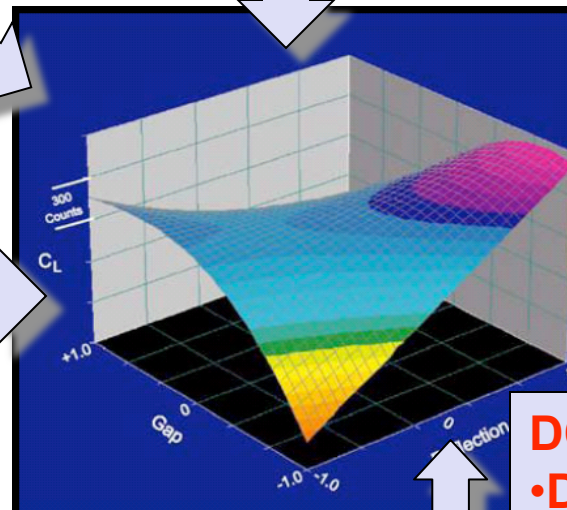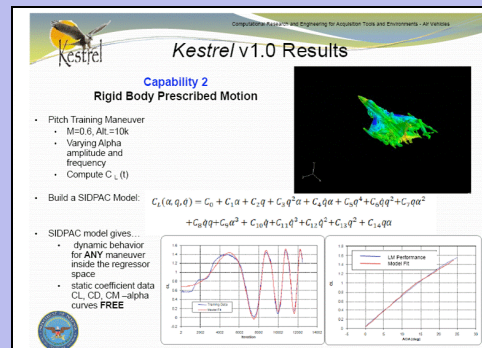# Streamlining Testing at the Campaign Level
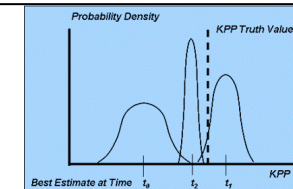## New T&E Tools + DOE

Common Thread System ID Techniques

Computational Science and Engineering Dynamic Trajectories

Estimation Theory Quantify Effectiveness of Testing

"Fly the Mission" Ground Testing

Kestrel v1.0 Results

Capability 2
Rigid Body Prescribed Motion

- Pitch Training Maneuver
  - M=0.6, Alt.=10k
  - Varying Alpha amplitude and frequency
  - Compute C_L (t)

- Build a SIDPAC Model: $C_L(\alpha, q, \dot{q}) = c_0 + c_1\alpha + c_2 q + c_3\dot{q}^2 + c_4 q\alpha + c_5 q^4 + c_6 q q^2 + c_7 q\alpha^2$
  $+ c_8 q q + c_9\alpha^3 + c_{10}\dot{q} + c_{11}q^2 + c_{12}q^2 + c_{13}q^2 + c_{14}q\alpha$

- SIDPAC model gives...
  - dynamic behavior for **ANY** maneuver inside the regressor space
  - static coefficient data CL, CD, CM –alpha curves **FREE**

Probability Density — **KPP Truth Value**

Best Estimate at Time — KPP

Using Estimation Theory* variance reduction is proportional to the effectiveness of resources used and resources applied

$$p(t_{i+1}) = p(t_i)/(1 + p(t_i)\, u\, \Delta t), \quad u = \text{resource effectiveness}$$
Or
$$u(t) = (p(t_i)/p(t_{i+1})-1)/p(t_i)\, \Delta t$$

Which can be estimated used the SEMP, TEMP, and KPP values pre- and post-test

Flight Testing

Value of T&E

DOE
- **Data Merge/Data Mine**
- **Response Surface Analysis**
- **Variance Reduction Strategy**

Kraft, Edward M. " Integrating Computational Science and Engineering with Testing to Re-engineer the Aeronautical Development Process,"
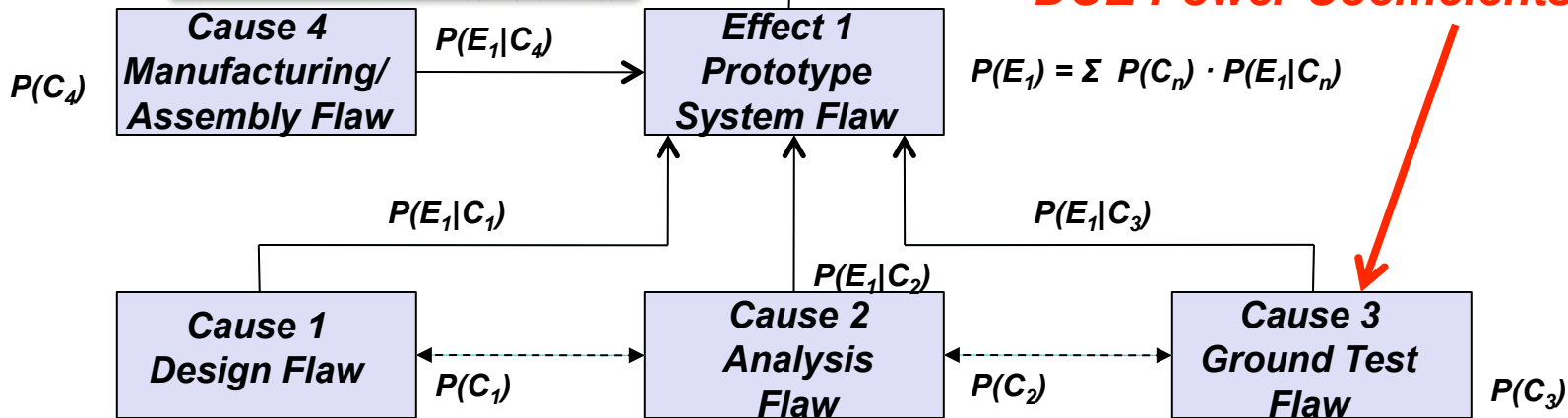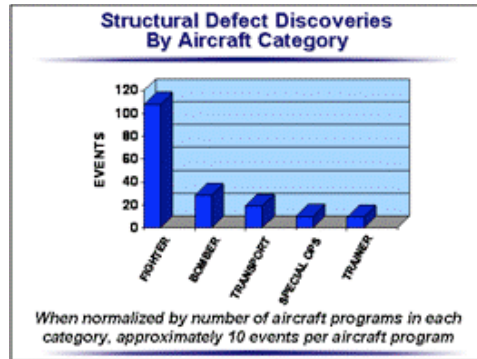AIAA Paper 2010-0139 , January, 2010

Reducing Late Defect Discoveries
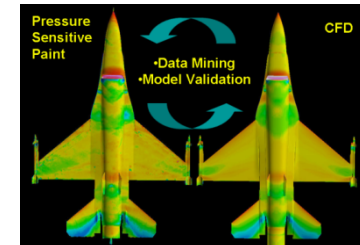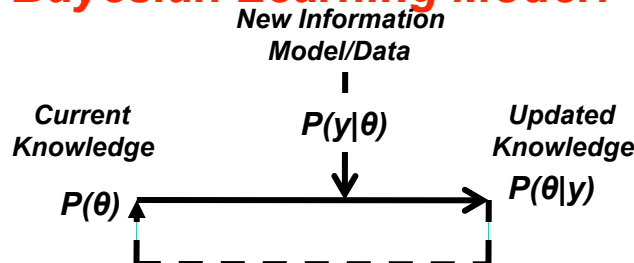# Bayesian Statistics + DOE

Increasing Costs of Defects

Bayesian Parameter Estimation for Risk Assessment

Structural Defect Discoveries By Aircraft Category

When normalized by number of aircraft programs in each category, approximately 10 events per aircraft program

Effect 2 Structural Flaw Found In Flight

$P(E_2|E_1)$

DOE Power Coefficients?

Cause 4 Manufacturing/ Assembly Flaw

$P(C_4)$

$P(E_1|C_4)$

Effect 1 Prototype System Flaw

$P(E_1) = \Sigma \; P(C_n) \cdot P(E_1|C_n)$

$P(E_1|C_1)$

$P(E_1|C_2)$

$P(E_1|C_3)$

Cause 1 Design Flaw

$P(C_1)$

Cause 2 Analysis Flaw

$P(C_2)$

Cause 3 Ground Test Flaw

$P(C_3)$

Bayesian Learning Model?

New Information Model/Data

Current Knowledge

$P(y|\theta)$

Updated Knowledge

$P(\theta)$

$P(\theta|y)$

Pressure Sensitive Paint
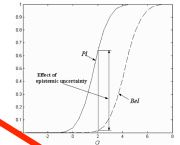
CFD

•Data Mining
•Model Validation
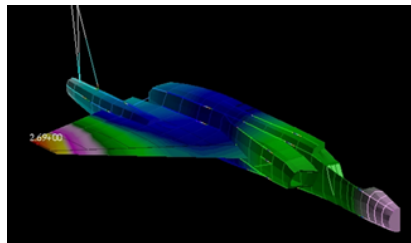
Probabilistic Incremental Development
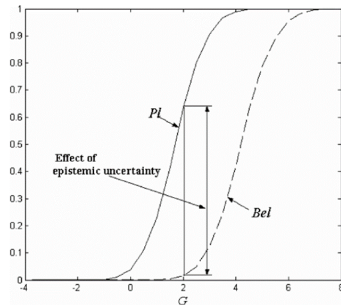# Merging Modeling and Testing
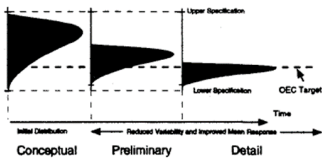
AFMC

System Level Metrics

$$\text{Range} = V \times (1/SFC) \times (L/D) \times \ln(We/Wf)$$

Evidence Theory

Epistemic Uncertainty

Aleatory Uncertainty

Bayes Theorem

Hypothesis: $p(\theta)$

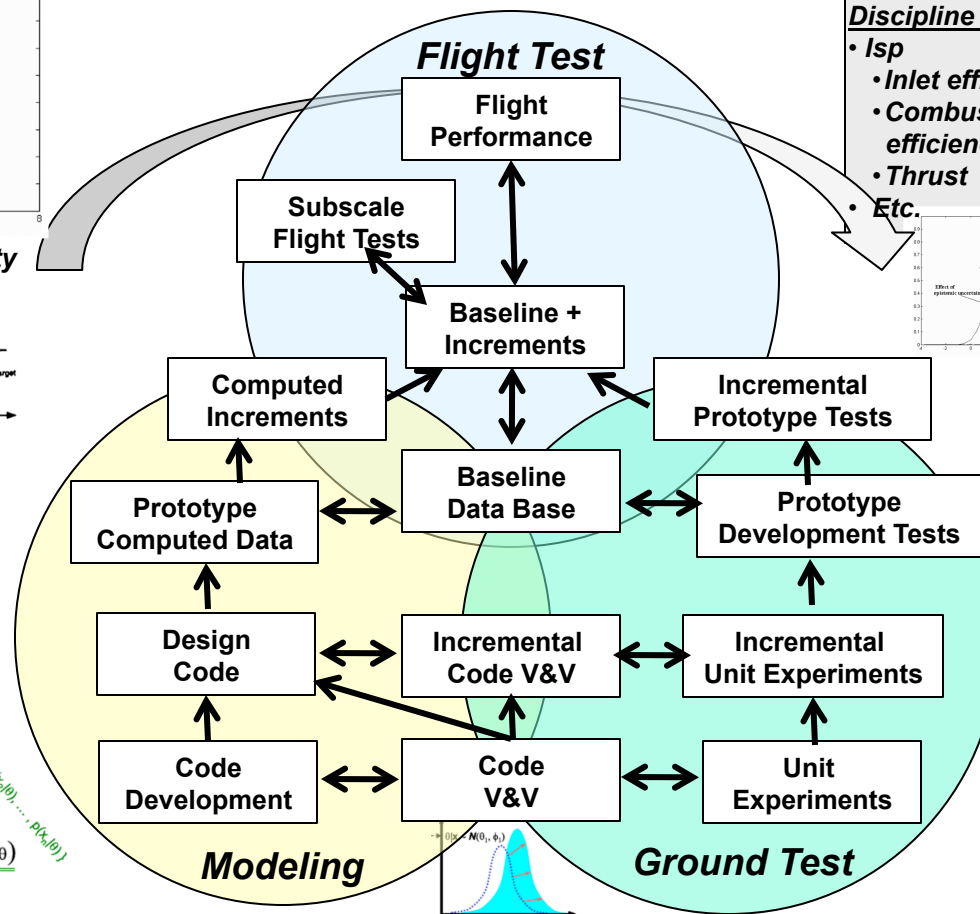Data: $p(x) = \int p(x_i|\theta) \cdot p(x_2|\theta)...$

$p(\theta|x_1) \propto p(\theta) \cdot p(x_1|\theta)$

$p(\theta|x_2) \propto p(\theta) \cdot p(x_2|\theta)$
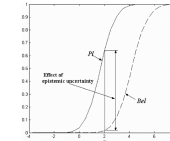
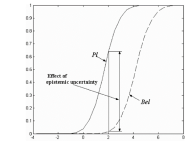$p(\theta|x_{...}) \propto p(\theta) \cdot p(x_{...}|\theta)$

Posterior Probability $p(\theta|x_n) \propto p(\theta) \cdot p(x_n|\theta)$

Flight Test

Flight Performance

Subscale Flight Tests

Baseline + Increments

Computed Increments

Incremental Prototype Tests

Baseline Data Base

Prototype Computed Data

Prototype Development Tests

Design Code

Incremental Code V&V

Incremental Unit Experiments

Code Development

Code V&V

Unit Experiments

Modeling

Ground Test

Recursively use all experimental data to V&V models

Propulsion
Discipline Metrics
- *Isp*
  - *Inlet efficiency*
  - *Combustion efficiency*
  - *Thrust*
- *Etc.*

Aerodynamics

Structures

Adapted/Merged from:
- Kraft, E. M., Chapman, G., "A Critical Review of the Integration of Computations, Ground Tests, and Flight Test for the Development of Hypersonic Vehicles," AIAA-93-51 01, Munich, Germany, Nov. 30-Dec. 3, 1993
- Mantis, G.C., Mavris, D. "A Bayesian Approach to Non-Deterministic Hypersonic Vehicle Design," AIAA Paper 2001-01-3033, 2001.
- Roy, C.J., Oberkampf, W.L. "A Complete Framework for Verification, Validation, and Uncertainty Quantification in Scientific Computing," AIAA Paper 2010-124, Presented at the 48th AIAA ASM Conference, Orlando, FL, January 2010.

Summary

- **Statistics and DOE is an increasingly important tool in T&E – best current value is *a priori* definition of data quality required**

- **T&E Community gaining expertise in DOE**

- **Applications of DOE in isolated tests currently produces marginal return to a program**
  - **Not pre-planned in TEMP**
  - **Inertia of conservative, legacy processes**

- **Integration of DOE with new T&E tools, Estimation Theory, and Bayesian Logic could amplify impact of DOE**

- **Best ROI for DOE needs to be based on acquisition program cycle time**